New Manufacturing Technologies

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INTRODUCTION

Driven by international competition and aided by application of computer technology, manufacturing firms have been pursuing two principal approaches during the 1980's:

* automation, and
* integration.

Automation is the substitution of machine for human function; integration is the reduction or elimination of buffers between physical or organizational entities. The strategy behind manufacturing firms' application of new automation technologies is multidimensional:

* to liberate human resources for knowledge work,
* to eliminate hazardous or unpleasant jobs,
* to improve product uniformity, and
* to reduce costs and variability.

The execution of that strategy has lead firms automate away simple, repetitive, or unpleasant functions in their offices, factories, and laboratories.

Integration, when used as an approach to improve quality, cost, and responsiveness to customers, requires that firms find ways to reduce physical, temporal, and organizational barriers among various functions. Such buffer reduction has been implemented by the elimination of waste, the substitution of information for inventory, the insertion of computer technology, or some combination of these.

In most **process** industries - oil refining and paper-making, for example - automation and integration have been critical trends for decades. However, in **discrete goods** manufacture - electronics and automobiles, for example - significant movement in these directions is a recent phenomenon in the United States.

This chapter defines, examines, and illustrates the application of technologies that support the trends toward more automation and integration in discrete goods manufacturing. We begin with a discussion of the technological hardware and software that has been evolving. We then look at six management challenges that must be addressed to support these trends. And, finally, we look at the issue of economic evaluation the new technologies.

AUTOMATION IN MANUFACTURING

As characterized, for example, by Toshiba, in their OME Works facility, automation in manufacturing can be divided into three categories:

*factory automation,
*engineering automation, and
*planning and control automation.

Automation in these three areas can occur independently, but coordination among the three, as is being pursued by this Toshiba facility, drives opportunities for computer-integrated manufacturing, discussed below.

Factory Automation

Although software also plays a critical role, factory automation is typically described by the technological hardware used in manufacturing: robots, numerically controlled (NC) machine tools, and automated material handling systems. Increasingly, these technologies are used in larger, integrated systems, known as manufacturing cells or flexible manufacturing systems (FMSs).

The term **robot** refers to a piece of automated equipment, typically programmable, that can be used for moving material to be worked on (pick and place) or assembling components into a larger device. Robots are also used to substitute for direct human labor in the use of tools or equipment, as is done, for example, by a painting robot, or a welding robot, which both positions the welder and welds joints and seams. Robots can vary significantly in complexity, from simple single-axis programmable controllers to sophisticated multi-axis machines with microprocessor control and real-time, closed-loop feedback and adjustment.

A **numerically-controlled (NC) machine tool** is a machine tool that can be run by a computer program that directs the machine in its operations. A stand-alone NC machine needs to have the workpieces, tools, and NC programs loaded and unloaded by an operator. However, once an NC machine is running a program on a workpiece, it requires significantly less operator involvement than a manually-operated machine.

A **CNC (computer numerically-controlled) machine tool** typically has a small computer dedicated to it, so that programs can be developed and stored locally. In addition, some CNC tools have automated parts loading and tool changing. CNC tools typically have real-time, on-line program development capabilities, so that operators can implement engineering changes rapidly.

A **DNC (distributed numerically-controlled) system** consists of numerous CNC tools linked together by a larger computer system that downloads NC programs to the distributed machine tools. Such a system is necessary for the ultimate integration of parts machining with production planning and scheduling.

Automated inspection of work can also be realized with, for example, vision systems or pressure-sensitive sensors. Inspection work tends to be tedious and prone to errors, especially in very high volume manufacturing settings, so it is a good candidate for automation. However, automated inspection (especially with diagnosis capability) tends to be very difficult and expensive. This situation, where automated inspection systems are expensive to develop, but human inspection is error-prone, demonstrates the value of automated manufacturing systems with very high reliability: In such systems, inspection and test strategies can be developed to exploit the high-reliability features, with the potential to reduce significantly the total cost of manufacture and test.

Automated material handling systems move workpieces among work centers, storage locations, and shipping points. These systems may include autonomous guided vehicles, conveyor systems, or systems of rails. By connecting separate points in the production system, automated material handling systems serve an integration function, reducing the time delays between different points in the production process. These systems force process layout designers to depict clearly the path of each workpiece and often make it economical to transport workpieces in small batches, providing the potential for reduced wait times and idleness.

A **flexible manufacturing system (FMS)** is a system that connects automated workstations with a material handling system to provide a multi-stage automated manufacturing capability for a wider range of parts than is typically made on a highly-automated, nonflexible, transfer line. These systems provide flexibility because both the operations performed at each work station and the routing of parts among work stations can be varied with software controls.

The promise of FMS technology is to provide the capability for flexibility approaching that available in a job shop with equipment utilizations approaching what can be achieved with a transfer line. In fact, an FMS is a technology intermediate to these two extremes, but good management can help in pushing both frontiers simultaneously.

Automated factories can differ significantly with respect to their strategic purpose and impact. Two examples, Matsushita and General Electric, may be instructive.

In Osaka, Japan, Matsushita Electric Industrial Company has a plant that produces video cassette recorders (VCRs). The heart of the operation features a highly automated robotic assembly line with 100-plus work stations. Except for a number of trouble-shooting operators and process improvement engineers, this line can run, with very little human intervention, for close to 24 hours per day, turning out any combination of 200 VCR models. As of August 1988, the facility was underutilized; Matsushita was poised to increase production, by running the facility more hours per month, as demand materialized.

In this situation, the marginal cost of producing more output is very low. Matsushita has effectively created a barrier to entry in the VCR industry, making it very difficult for entrants to compete on price.

The second example is General Electric's Aircraft Engine Group Plant III, in Lynn, Massachusetts. This fully automated plant machines a small set of parts used by the Aircraft Engine Group's assembly plant. In contrast to Matsushita's plant, which provides strategic advantage in the VCR **product** market, the strategic advantage provided by GE's plant seems to address its **labor** market. Plant III's investment is now sunk. Eventually, it will run around the clock at very high utilization rates with a very small crew. As volume is ramped up, GE has the ability to use Plant III's capacity and cost structure as leverage with its unionized labor force which is currently making many of the parts that could eventually be transferred to Plant III. Thus, factory automation can address a variety of types of strategic needs, from product market considerations to labor market concerns.

Engineering Automation

From analyzing initial concepts to finalizing process plans, engineering functions that precede and support manufacturing are becoming increasingly automated. In many respects, engineering automation is very similar to factory automation; both phenomena can dramatically improve labor productivity and both increase the proportion of knowledge work for the remaining employees. However, for many companies, the economic payback structure and the justification procedures for the two technologies can be quite different.

This difference between engineering automation and factory automation stems from a difference in the scale economies of the two types of technologies. In many settings, the minimum efficient scale for engineering automation is quite low. Investment in an engineering workstation can often be justified whether or not it is networked and integrated into the larger system. The first-order improvement of the engineer's productivity is sufficient.

For justification of factory automation, the reverse is more frequently the case. The term "island of automation" has come to connote a small investment in factory automation that, by itself, provides a poor return on investment. Many firms believe that factory automation investments must be well integrated and widespread in the operation before the strategic benefits of quality, lead time, and flexibility manifest themselves.

Computer-aided design is sometimes used as an umbrella term for computer-aided drafting, computer-aided engineering analysis, and computer-aided process planning. These technologies can be used to automate significant amounts of the drudgery out of engineering design work, so that engineers can concentrate more of their time and energy on being creative and evaluating a wider range of possible design ideas. For the near future machines will not typically design products. The design function remains almost completely within the human domain.

Computer-aided engineering allows the user to apply necessary engineering analysis, such as finite element analysis, to propose designs while they are in the drawing-board stage. This capability can reduce dramatically the need for time-consuming prototype workup and test during the product development period.

Computer-aided process planning helps to automate the manufacturing engineer's work of developing process plans for a product, once the product has been designed.

Planning and Control Automation

Planning and control automation is most closely associated with material requirements planning (MRP). Classical MRP develops production plans and schedules by using product bills of materials and production lead times to explode customer orders and demand forecasts netted against current and projected inventory levels. MRP II systems (second-generation MRP) are manufacturing resource planning systems that build on the basic MRP logic, but also include modules for shop floor control, resource requirements planning, inventory analysis, forecasting, purchasing, order processing, cost accounting, and capacity planning in various levels of detail.

The economic considerations for investment in planning and control automation are more similar to that for investment in factory automation than that for engineering automation. The returns from an investment in an MRP II system can only be estimated by analyzing the entire manufacturing operation, as is also the case for factory automation. The integration function of the technology provides a significant portion of the benefits.

INTEGRATION IN MANUFACTURING

Four important movements in the manufacturing arena are pushing the implementation of greater integration in manufacturing:

* Just-in-Time manufacturing (JIT),
* Design for Manufacturability (DFM),
* Quality Function Deployment (QFD), and
* Computer-integrated Manufacturing (CIM).

Of these, CIM is the only one directly related to new computer technology. JIT, QFD, and DFM, which are organization management approaches, are not inherently computer-oriented and do not rely on any new technological developments. We will look at them briefly here because they are important to the changes that many manufacturing organizations are undertaking and because their integration objectives are very consonant with those of CIM.

Just-in-Time Manufacturing (JIT)

JIT embodies the idea of pursuing streamlined or continuous-flow production for the manufacture of discrete goods. Central to the philosophy is the idea of reducing manufacturing setup times, variability, inventory buffers, and lead times in the entire production system, from vendors through to customers, in order to achieve high product quality (conformity), fast and reliable delivery performance, and low costs.

The reduction of time and inventory buffers between work stations in a factory, and between a vendor and its customers, creates a more integrated production system. People at each work center develop a better awareness of the needs and problems of their predecessors and successors. This awareness, coupled with a cooperative work culture, can help significantly with quality improvement and variability reduction.

Investment in technology, that is, machines and computers, is not required for the implementation of JIT. Rather, JIT is a management technology that relies primarily on persistence in pursuing continuous incremental improvement in manufacturing operations. JIT accomplishes some of the same integration objectives achieved by CIM, without significant capital investment. Just as it is difficult to quantify the costs and benefits of investments in (hard) factory automation, it is also difficult to quantify costs and benefits of a "soft" technology such as JIT. A few recent models have attempted to do such a quantification, but that body of work has not been widely applied.

Design for Manufacturability (DFM)

This approach is sometimes called concurrent design or simultaneous engineering. DFM is a set of concepts related to pursuing closer communication and cooperation among design engineers, process engineers, and manufacturing personnel. In many engineering organizations, traditional product development practice was to have product designers finish their work before process designers could even start theirs. Products developed in such a fashion would inevitably require significant engineering changes as the manufacturing engineers struggled to find a way to produce the product in volume at low cost with high uniformity.

Quality Function Deployment (QFD)

Closely related to Design for Manufacturability is the concept of Quality Function Deployment (QFD) which requires increased communication among product designers, marketing personnel, and the ultimate product users. In many organizations, once an initial product concept was developed, long periods would pass without significant interaction between marketing personnel and the engineering designers. As a result, as the designers confronted a myriad of technical decisions and tradeoffs, they would make choices with little marketing or customer input. Such practices often led to long delays in product introduction because redesign work was necessary once the marketing people finally got to see the prototypes. QFD formalizes interaction between marketing and engineering groups throughout the product development cycle, assuring that design decisions are made with full knowledge of all technical and market tradeoff considerations.

Taken together, Design for Manufacturability and Quality Function Deployment promote integration among engineering, marketing, and manufacturing to reduce the total product development cycle and to improve the quality of the product design, as perceived by both the manufacturing organization and the customers who will buy the product.

Like Just-in-Time, Design for Manufacturability and Quality Function Deployment are not primarily technological in nature. However, technologies such as Computer-aided Design can often be utilized as tools for fostering engineering/manufacturing/marketing integration. In a sense, such usage can be considered as the application of computer-integrated manufacturing to implement these policy choices.

Computer-integrated Manufacturing (CIM)

Computer-integrated manufacturing refers to the use of computer technology to link together all functions related to the manufacture of a product. CIM is therefore both an information system and a manufacturing control system. Because its intent is so all-encompassing, even describing CIM in a meaningful way can be difficult.

We describe briefly one relatively simple conceptual model that covers the principal information needs and flows in a manufacturing firm. The model consists of two types of system components:

* departments that supply and/or use information, and
* processes that transform, combine, or manipulate information in some manner.

The nine departments in the model are:

1. production
2. purchasing
3. sales/marketing
4. industrial amd manufacturing engineering
5. product design engineering
6. materials management and production planning
7. controller/finance/accounting
8. plant and corporate management
9. quality assurance.

The nine processes that transform, combine, or manipulate information in some manner are:

1. cost analysis
2. inventory analysis
3. product line analysis
4. quality analysis
5. workforce analysis
6. master scheduling
7. material requirements planning (MRP)
8. plant and equipment investment

9. process design and layout.

To complete the specification of the model for a specific manufacturing system, one must catalog the information flows among the departments and information processes listed above. Such an information flow map can serve as a conceptual blueprint for CIM design, and can aid in visualizing the scope and function of a CIM information system.

Design and implementation of a computer system to link together all of these information suppliers, processors, and users is typically a long, difficult, and expensive task. Such a system must serve the needs of a diverse group of users, and must typically bridge a variety of different software and hardware subsystems.

The economic benefits from such a system come from faster and more reliable communication among employees within the organization and the resulting improvements in product quality and lead times.

Since many of the benefits of a CIM system are either intangible or very difficult to quantify, the decision to pursue a CIM program must be based on a long term, strategic commitment to improve manufacturing capabilities. Traditional return-on-investment evaluation procedures that characterize the decision-making processes of many U.S. manufacturing concerns will not justify the tremendous amount of capital and time required to aggressively pursue CIM. Despite the high cost and uncertainty associated with CIM implementation, most large U.S. manufacturing companies are investing some resources to explore the feasibility of using computerized information sytems to integrate the various functions of their organizations.

TECHNOLOGY ADOPTION CONSEQUENCES: FLEXIBILITY AND CAPITAL INTENSIVENESS

As explained above, investments in factory automation and CIM move a firm in the direction of more automation and integration. To fully evaluate such investment opportunities, and to weigh the potential pay-offs against the costs, one must consider two consequences of these technologies:

1) the flexibility of the manufacturing operation, and
2) the capital intensiveness of the operation.

In this section, we look briefly at these two effects before discussing six challenges created by the new manufacturing technologies.

Manufacturing **flexibility** - flexibility to change product mix, to change production rate, and to introduce new products - is achieved by shortening lead times within the manufacturing system and by automating setups and changeovers for different products. The importance of manufacturing flexibility for firm competitiveness has become apparent over the past decade as the rate of economic and technological change has accelerated and as many consumer and industrial markets have become increasingly internationalized.

As a consequence of this increased competition, product life cycles shorten as each firm tries to keep up with the new offerings of a larger group of industrial rivals.

To survive, companies must respond quickly and flexibly to competitive threats. Therefore, firms must pay particular attention to evaluating the flexibility component of the new manufacturing technologies.

Increased **capital intensiveness** follows directly from automation on a large scale that replaces humans with machines. A transformation to a capital intensive cost structure has two important effects.

First, the manufacturing cost structure changes, from one with low fixed investment and high unit variable costs, to one with high fixed investment and low variable costs. This change will affect significantly a firm's ability to weather competitive challenges, because low variable costs allow a firm to sustain short-term profitability even in the face of severe price wars.

Second, the changes in both employment levels and work responsibilities brought about by automation require significant organizational adjustment. Challenges brought about by this type of change are discussed below.

SIX CHALLENGES CREATED BY THE NEW MANUFACTURING TECHNOLOGIES

1.Design and Development of CIM Systems

Because of their ambitious integration objectives, CIM systems will be large, complex information systems. Ideally, the design process should start with the enunciation of the CIM mission, followed by a statement of specific goals and tasks. Such a top-down design approach insures that the hardware and software components are engineered into a cohesive system.

In addition, since the foundation of CIM consists of an integrated central database plus distributed databases, database design is critical. Also, since many people in the organization will be responsible for entering data into the system, they must understand how their functions interact with the entire system. Input from users must be considered at the design stage, and systems for checking database accuracy and integrity must be included.

Hardware and software standardization must also be considered at the system design stage. At many companies, computing and database capabilities have come from a wide variety of vendors whose products are not particularly compatible. Either retooling, or developing systems to link these computers together, requires significant resources.

Obviously, designing a system that will be recognized as a success, both inside and outside the organization, is a formidable challenge. Few, if any, companies have fully accomplished this task to date.

2. Human Resource Management System

As mentioned above, significant adjustment is required for an organization to coalesce behind the implementation of new factory automation and CIM technology. If the new technology is not installed in a greenfield site, then layoffs are often one consequence of the change. Reductions in force are inevitably associated with morale problems for the remaining employees who may view the layoffs as a sign of corporate retreat rather than revitalization.

Furthermore, human resource problems are not typically limited to simply laying off a set number of people and then just moving forward with the remaining group. CIM and automation technologies place significantly greater skill demands on the organization. Retraining and continuous education must be the rule for firms that hope to be competitive with these technologies; the firm must undergo a cultural transformation.

Requirements for retraining and continuous education are at least as strong for managers and engineers who work with these new technologies as for the factory workers on the plant floor. Designing automated factories, managing automated factories, and designing products for automated factories all require supplemental knowledge and skills compared with those required for a traditional, labor-intensive plant. Senior managers, who must evaluate CIM technologies, as well as the people who work with them, also can benefit significantly from education about the technologies.

3. Product Development System

Factory automation and CIM can make product designers' jobs more difficult. Human-driven production systems are infinitely more adaptable than automated manufacturing systems. When designers are setting requirements for a manually built product, they can afford some sloppiness in the specifications, knowing that the human assemblers can either accomodate unexpected machining or assembly problems as they occur, or at least can recognize problems and communicate them back to the designers for redesign.

In an automated setting, designers cannot rely on the manufacturing system to easily discover and recover from design errors. There are severe limits to the levels of intelligence and adaptability that can be designed into automated manufacturing systems, so product designers must have either intimate knowledge of the manufacturing system or intimate communication with those who do. Developing such a design capability in the organization is a difficult, but necessary step for achieving world-class implementation of the manufacturing system.

4. Managing Dynamic Process Improvement

In most well-run, labor-intensive manufacturing systems, continuous improvement results from a highly motivated workforce that constantly strives to discover better methods for performing its work. In a highly automated factory, there are few workers to observe, test, experiment with, think about, and learn about the system and how to make it better. As a consequence, some observers claim that factory automation will mean the end of the learning curve as an important factor in manufacturing competitiveness. Such an assertion runs counter to a very long history of progress in industrial productivity, resulting from a collection of radical technological innovations, each followed by an extensive series of incremental improvements that help perfect the new technology. Most students of the subject estimate that the accumlation of such incremental improvements accounts for as much total productivity growth as do the radical innovations. In essence, any radical innovation may be thought of as a first pass innovation which requires much more innovation before it reaches its maximum potential.

To presume that factory automation and CIM will reverse this historic pattern is premature at best, and potentially very misleading to managers and implementers of these technologies. Because these technologies are so new and so complex, one cannot expect to capture all of the relevant knowledge at the system design stage. If a firm assumes that once it is in place, the technology will not be subject to very much improvement, it will evaluate, design, and manage the system much differently than if it assumes that much benefit can be achieved by learning more about how best to use and improve the system once it is in place. One might expect to observe self-fulfilling prophecies in this regard. Even though an automated factory has far fewer people (potential innovators) in it, firms who invest in this technology would be wise to assure that those people who **are** present are trained to discover, capture, and apply as much new knowledge as possible. In fact, discovering and exploiting opportunities for continuous improvement might be the primary reasons for firms to avoid completely unattended factories.

5. Technology Procurement

Before evaluating a specific technological option, that option must be reasonably well defined. A firm needs to choose equipment and software vendors, and to decide how much of the design, production, installation, and integration of the technology will be performed with in-house staff. Many observers argue for doing as much technology development in house as possible, to minimize information leaks about the firm's process technology, and to assure a proper fit between the firm's new technology and its existing strategy, people, and capital assets.

For external technology acquisition, technological options must be generated before they can be evaluated. In developing these options, a firm must consider its current assets, environment, and market position, as well as those of its competitors. Equipment vendors must be brought into the decision process. Vendor and technology evaluation criteria must be developed and utilized within the organization.

6. System Control and Performance Evaluation

Once a technology investment choice has been implemented, managers typically want to track the efficacy of that investment. The shortcomings of the traditional methods for measuring manufacturing performance are widely recognized. Many of these methods can be manipulated to make current results look good at the expense of potential future results. When managers spend only a small fraction of their careers in one facility or position, they often have an incentive to engage in such manipulations. In addition, in many settings, the appropriate performance yardstick for a facility requires information on one or more competitors' facilities, on which timely, accurate data may be unavailable.

Increasingly, firms are using multidimensional measures of manufacturing performance. Rather than depending on just a profitability summary statistic, measures of quality, lead times, cost of quality, delivery performance, and total factor productivity are being utilized to evaluate performance. Despite this trend, firms could benefit from more research on how, for example, to set standards for productivity and learning rates in a highly automated, integrated environment.

ECONOMIC EVALUATION FOR NEW TECHNOLOGY ADOPTION

The technology adoption costs that are the most visible and easiest to estimate in advance are the up-front capital outlays for purchased hardware, software, and services. Most models consider only these costs. Also important, however, are (1) costs of laying off people whose skills will not be used in the new system, (2) costs of plant disruption caused by the introduction of new technology into an operating facility, and (3) costs of developing the human resources required to design, build, manage, maintain, and operate the new system.

The benefits that flow from investment in factory automation and CIM are both tactical and strategic. These benefits relate to changes in a firm's cost structure, increased process repeatability and product conformance, lower inventories, increased flexibility, and shorter flow and communication lines.

With respect to cost structure, investment in CIM and factory automation tends to represent a large up-front cost that leads to a reduction in variable costs per unit of output. This characteristic results primarily from replacement of labor by machines. Low variable costs can provide significant competitive advantage when interfirm rivalry is high. In addition, reduced variable costs sometimes lead firms to cut prices, potentially increasing market share and revenues.

The advantages arising from the increased repeatability and product conformance afforded by CIM and factory automation can also have significant competitive impact. Decreased process variability reduces scrap and rework costs, a source of variable cost savings that can be as important as the reduction of direct labor costs by automation. In addition, improved product conformance can provide significant sales gains in product markets.

Secondary effects of improved process control include improved morale (and consequent reduced absenteeism and turnover) of employees happy to work in a system that runs well.

Inventory reduction following automation and integration investments can originate from several sources. First, factory automation can reduce setup times for some types of operations, reducing the need for cycle stocks. Second, decreased process variability can decrease uncertainty in the entire manufacturing system, reducing the need for safety stocks. Third, factory integration can shorten manufacturing cycle times, reducing the in-process inventories flowing through the system.

Manufacturing flexibility is another key strategic advantage offered by CIM and factory automation. Rapid tool and equipment changeovers enable firms to quickly change product mix in response to varying market demands. In addition, NC programming and computerized process planning shorten the time to market and time to volume for new products introduced into the factory. Fully-automated manufacturing systems provide volume flexibility as well. The highly-automated Matsushita VCR factory mentioned earlier can change its output rate with relatively low adjustment costs by increasing or decreasing the number of hours it runs each month. Because the factory's direct labor force is quite small, output declines will not lead to dramatic underemployment, and increases do not require major hiring and training efforts.

Finally, reduced lead times between work stations will lower the flow times of work between stations, thus decreasing the need for WIP in the system. As inventories and lead times are reduced, firms may increase their profit margins by charging more for rapid delivery or may increase market share by offering better service and holding prices constant.

SUMMARY AND CONCLUSIONS

Increased global competition and environmental volatility require that firms adapt quickly or face the possibility of extinction. Investment in automation and integration, including hardware such as automated machines and flexible manufacturing systems, software such as CIM systems, and managerial approaches such as just-in-time and design for manufacturability, can help firms to achieve and maintain competitiveness.

Of course, the assets always in shortest supply are managerial vision and leadership. Manufacturing strategy creation must precede technology investment decisions, because good technology rarely saves poor management. Therefore, firms must complement their learning about technology options with information and insights about their business challenges and opportunities.

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